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# Optimizing hybrid supercapacitor performance through synergistic integration of metal–organic frameworks and metal oxides

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Metal–organic frameworks (MOFs) offer significant advantages for energy storage, including high surface area, customizable porosity, and abundant active sites. We utilized these properties to synthesize a novel barium-MOF and neodymium oxide composite (Ba-MOF/Nd<sub>2</sub>O<sub>3</sub>) as an electrode material for hybrid supercapacitors. Incorporating Nd<sub>2</sub>O<sub>3</sub>—a lanthanide-series rare-earth metal oxide—enhances the composite's electrochemical properties, particularly in terms of specific capacity, energy density, power density, and cyclic stability. In a half-cell setup, the composite provided a remarkable specific capacity of 718 C g<sup>-1</sup> at the lowest current density (1.9 A g<sup>-1</sup>). For further investigation, a real device was functionalized, which provided better energy density of 96 Wh kg<sup>-1</sup> with a maximum power density of 9350 W kg<sup>-1</sup>. The device exhibited a rate capability of 96% and capacity retention of 92%, even after the 5000 charge–discharge process. Furthermore, semi-empirical models were employed to assess the capacitive and diffusive contributions.

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## 1. Introduction

In the developing world, the growing use of electrical appliances has led to an increasing demand for electrical energy.<sup>1</sup> Non-renewable resources are inadequate to meet this demand owing to depletion and ecological concerns.<sup>2,3</sup> Renewable

energy resources exhibit unstable availability and inconsistency. Consequently, they require intermediate storage solutions for consistent power supply.<sup>4,5</sup> In the realm of electrochemical energy storage devices (EESDs), supercapacitors (SCs) and rechargeable batteries (RBs) are leading trends owing to their superior electrochemical performance and potential to mitigate the energy crisis.<sup>6–8</sup> Batteries excel in energy density and specific capacity, but several factors, such as low power, lower lifespan, and safety hazards, hamper their practical applications. Conversely, although SCs are known for their high power density, durability, and environmental friendliness, their low energy density constrains their application.<sup>9,10</sup> Consequently, each technology alone cannot fully meet the commercial requirements. To address these challenges, engineers have developed hybrid energy storage devices that combine the strengths of supercapacitors and rechargeable batteries known as hybrid supercapacitors (HSCs).<sup>11–13</sup>

An effective strategy to boost the performance of HSCs is to endow an electrode material with superior electrochemical properties.<sup>2,14</sup> Various electrode materials have been explored to enhance the electrochemical performance of HSCs, including conducting polymers,<sup>15,16</sup> carbon-based material,<sup>17–20</sup> layered hydroxide,<sup>21,22</sup> transition metal oxides,<sup>23,24</sup> phosphates,<sup>25,26</sup> sulfides<sup>27–29</sup> and selenides.<sup>30</sup> Despite these materials, metal–organic frameworks (MOFs) have attracted significant attention as energy storage systems due to their exceptional structural and functional attributes.<sup>31–33</sup> The metal–ligand structure provides a remarkably high surface area, crucial for maximizing

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active sites involved in electrochemical reactions.<sup>34</sup> The high surface area and adjustable porosity enable efficient electrolyte transport and enhanced charge storage capacity. The tunable porosity of MOFs allows for customization of their properties to meet specific energy storage requirements.<sup>35</sup> Despite these advantages, some pristine MOFs are often limited by poor electrical conductivity and instability, which can affect their efficiency in energy storage solutions.<sup>36,37</sup>

Alkaline earth metals (AEMs) such as radium, strontium, and barium are important for creating MOFs due to their divalent nature and large ionic size, which support the development of stable architectures.<sup>38</sup> In particular, barium shows great promise in energy storage applications. Its larger ionic radius enables a highly adaptable coordination environment, which allows the creation of diverse and stable structural frameworks with enhanced porosity and surface area. Besides, carboxylate ligands are excellent at coordinating with metal ions through their oxygen atoms, providing multiple binding sites that enable the formation of large and stable networks.<sup>39</sup> These ligands are suitable for building MOFs because they establish strong connections with metal ions.<sup>40</sup> Despite their remarkable properties, pristine MOFs face several limitations that hinder their performance in energy storage systems. They typically exhibit low electrical conductivity, limited ion diffusion, and reduced mechanical strength, which can lead to poor long-term capacity retention.<sup>36</sup>

Besides, metal oxides—particularly those from the rare-earth lanthanide series—offer several advantages for energy storage applications. Their high reactivity, large surface-to-volume ratio, and catalytic properties contribute to improved charge storage capacity and energy density. However, their application can be constrained by high costs and limited availability. Furthermore, metal oxides can suffer from reduced durability in energy storage applications owing to their highly reactive nature. Hybridizing MOFs with functional materials such as metal oxides to create composites mitigates the shortcomings of parent materials.<sup>41,42</sup>

Herein, the synthesis of Ba-MOF was carried out through hydrothermal treatment, followed by the fabrication of a composite incorporating commercially available neodymium oxide (Nd<sub>2</sub>O<sub>3</sub>). Subsequently, the composite was employed as an electrode material to strengthen the electrochemical response of the hybrid supercapacitor. The incorporation of Nd<sub>2</sub>O<sub>3</sub> not only enhances the structural stability of the composite but also improves its electrochemical performance. The composite demonstrated superior performance, attaining a specific capacity ( $Q_s$ ) of 718 C g<sup>-1</sup> ( $C_s$  of 1026 F g<sup>-1</sup>) at 1.9 A g<sup>-1</sup>. To assess the practical applicability of the composite, an HSC device was assembled, delivering the energy density ( $E_d$ ) of 96 Wh kg<sup>-1</sup> with a power density ( $P_d$ ) of 765 W kg<sup>-1</sup> at a current density of 0.9 A g<sup>-1</sup>. Furthermore, the device achieved the highest  $P_d$  of 9350 W kg<sup>-1</sup> while preserving the  $E_d$  of 26 Wh kg<sup>-1</sup> at 11 A g<sup>-1</sup>. For examination of capacitive and diffusive contributions in full-cell assembly, theoretical models (*i.e.*, linear and quadratic models) were compared. The findings suggest that Ba-MOF/Nd<sub>2</sub>O<sub>3</sub> holds significant potential as an electrode for future energy storage technology.

## 2. Experimental procedure

### 2.1. Materials

All available solvents, metal salts, binders, electrolytes, and metal salts were utilized without additional refinement. The reagents included barium chloride (BaCl<sub>2</sub>), trimesic acid, nickel foam, *N*-methyl-2-pyrrolidone (NMP), polyvinylidene fluoride (PVDF), acetylene black, and potassium hydroxide (KOH), all obtained from Urich Technology. The other chemicals were sourced from Sigma-Aldrich, including hydrochloric acid (HCl, 37%) and dimethyl formamide (DMF).

### 2.2. Synthesis of Ba-MOF

To synthesize Ba-MOF, 0.5 M of BaCl<sub>2</sub> was first dissolved in 20 mL of deionized water and ultrasonicated for 30 min. Simultaneously, 0.3 M of trimesic acid was poured into another beaker with 15 mL of deionized water and stirred for 30 min. For the uniform dispersion of trimesic acid, 5 mL of DMF was also added. Then, the solutions were gradually combined while stirring. After the complete dissolution and uniformity, the precursor solution was placed in an autoclave and calcined at 180 °C for 24 h. The product was obtained through centrifugation and thoroughly rinsed with methanol and deionized water. Ultimately, the material was dried at 70 °C overnight in a furnace.<sup>43,44</sup>

### 2.3. Synthesis of Ba-MOF/Nd<sub>2</sub>O<sub>3</sub>

Ba-MOF/Nd<sub>2</sub>O<sub>3</sub> was synthesized by dissolving 0.5 M of commercially sourced Nd<sub>2</sub>O<sub>3</sub> in 20 mL of deionized (DI) water, followed by stirring on a magnetic stirrer. In a separate beaker, 0.3 M BaCl<sub>2</sub> was dissolved in 15 mL of DI water and stirred. Concurrently, 0.2 M trimesic acid was added to a mixture of 15 mL of DI water and DMF and stirred for 30 minutes to ensure complete dissolution. Once prepared, the BaCl<sub>2</sub> solution was slowly introduced into trimesic acid solution while stirring to achieve thorough mixing. Subsequently, the Nd<sub>2</sub>O<sub>3</sub> solution was gradually added to the combined mixture, ensuring homogeneous dispersion. Following this, the prepared solution was introduced into an autoclave and annealed at 180 °C for 24 h. Subsequent steps followed the same protocol described for Ba-MOF synthesis. The experimental work is portrayed in Fig. 1.

### 2.4. Electrode fabrication

For electrode preparation, nickel foam (NF) with dimensions of (1 × 1.5 cm<sup>2</sup>) were used as the substrate to assess the electrochemical performance of the synthesized materials. Ten mL slurries were prepared for each electrode, containing 80 wt% of active materials, 10 wt% of acetylene black, and 5 wt% of both PVDF and NMP. Subsequently, the slurries were stirred for 6 hours to prepare a homogeneous solution. Then, the prepared solutions were deposited onto NF, covering it half-length (1 × 0.75 cm<sup>2</sup>) by utilizing a micropipette. Finally, the electrodes were dried in a furnace at 70 °C for 4 h.<sup>45</sup>

To assess the real device, a cathodic electrode (AC) was fabricated with PVDF, AC, NMP, and acetylene black using the



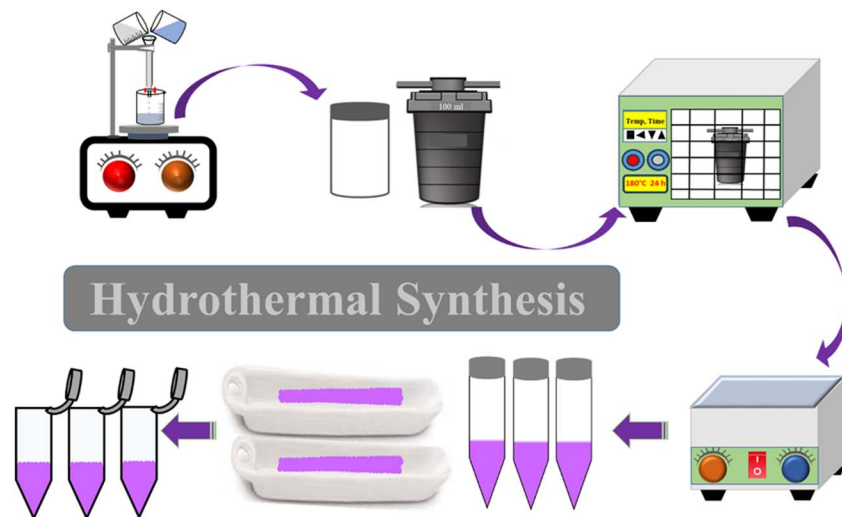


Fig. 1 Schematic illustrating the synthesis of electrode materials.

previously described method. The mass balance was calculated using the equation given below:<sup>46</sup>

$$\frac{m_+}{m_-} = \frac{C_{s_-} \times \Delta V_-}{C_{s_+} \times \Delta V_+} \quad (1)$$

Here  $m_+$  and  $C_+$  are the mass loading and capacitance of the anodic electrode, respectively, while  $m_-$  and  $C_-$  denote the mass loading and capacitance of the cathodic electrode, respectively.

## 3. Results and discussion

### 3.1. Physicochemical characterization

X-ray diffraction (XRD) was conducted to examine the structural order and phase composition of the fabricated materials. Fig. 2(a) shows the XRD pattern of Ba-MOF, revealing its cubic crystalline structure with well-defined peaks indexed according to (JCPDS 96-900-8529).<sup>47</sup> The sharpness and high intensity of

the peaks suggest good crystallinity and phase purity of the material. Similarly, the XRD pattern of  $\text{Nd}_2\text{O}_3$  exhibits distinct peaks indexed according to (JCPDS 00-043-1023),<sup>48</sup> revealing its hexagonal crystalline structure, as portrayed in Fig. 2(b). Fig. 2(c) presents the XRD pattern of Ba-MOF/ $\text{Nd}_2\text{O}_3$  with well-defined peaks corresponding to both Ba-MOF and  $\text{Nd}_2\text{O}_3$ , confirming the coexistence of the two phases within the composite material. The small shift in some XRD peaks of the composite is likely due to lattice strain, partial diffusions, or partial diffusion of  $\text{Nd}^{3+}$  ions into the Ba-MOF structures. Additionally, internal stress, defects, or changes in crystallite size could contribute to this shift.<sup>49</sup> The peak's sharpness and consistency reveal good crystallinity, suggesting that both components retained their structural integrity during composite formation.

Fig. 2(d–h) provides the intricate spatial distribution of the elements present within the material, especially Ba, C, O, and Nd. The observed slight inhomogeneity in elemental

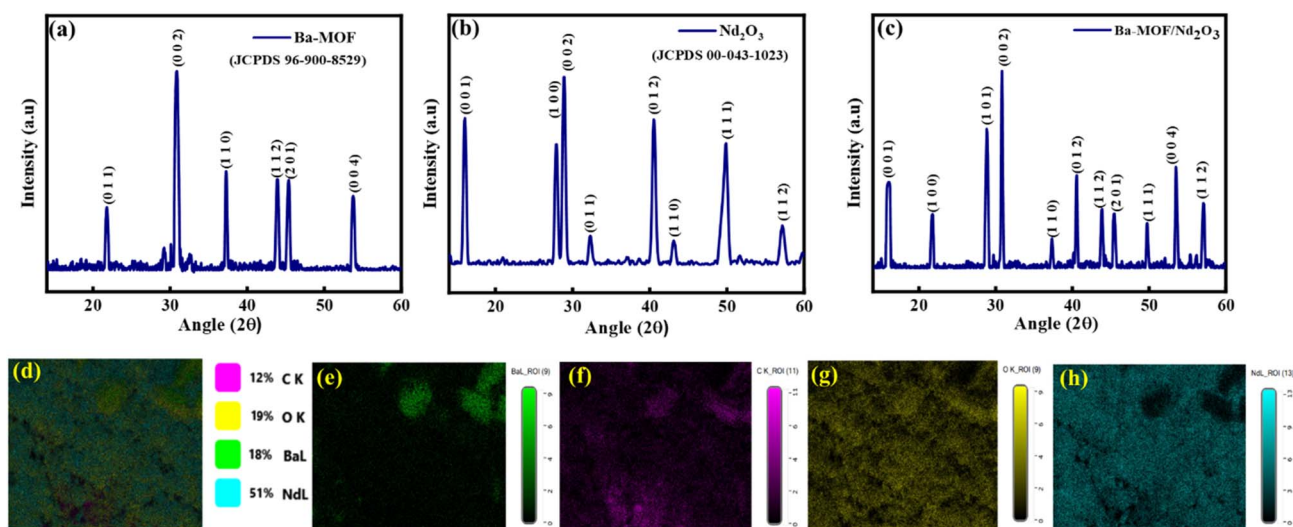


Fig. 2 (a) XRD patterns of Ba-MOF (b)  $\text{Nd}_2\text{O}_3$  (c) Ba-MOF/ $\text{Nd}_2\text{O}_3$  composite. (d–h) Elemental mapping of the Ba-MOF/ $\text{Nd}_2\text{O}_3$  composite.



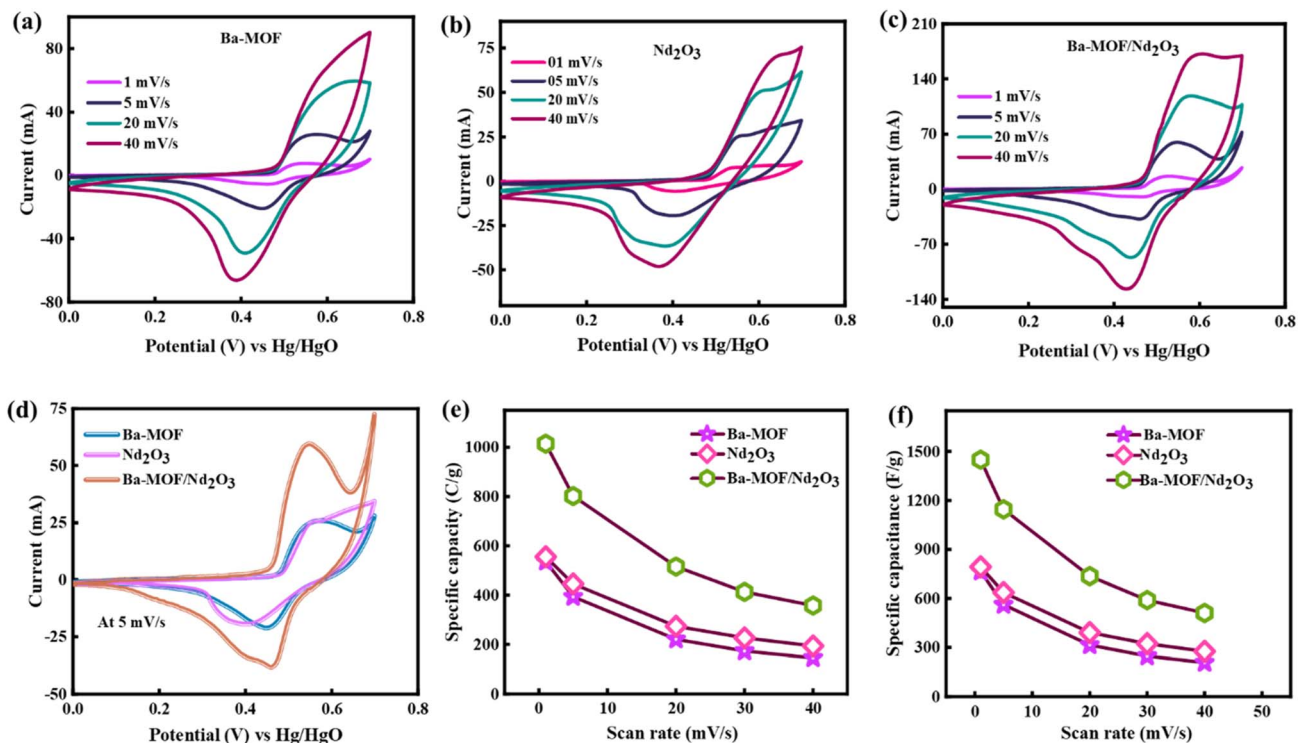


Fig. 3 Cyclic curves of (a) Ba-MOF (b)  $\text{Nd}_2\text{O}_3$  (c) Ba-MOF/ $\text{Nd}_2\text{O}_3$  at various scan rates. (d) Comparative CV at  $5 \text{ mV s}^{-1}$ . (e)  $Q_s$  of fabricated electrodes through CV at various scan rates. (f)  $C_s$  of fabricated electrodes through CV at various scan rates.

distribution may be attributed to surface roughness and local agglomeration of  $\text{Nd}_2\text{O}_3$  within the Ba-MOF framework; however, the presence of all key elements confirms successful composite formation. Better homogeneity is achieved during

the slurry preparation process for electrochemical testing, where uniform mixing ensures consistent electrode performance.

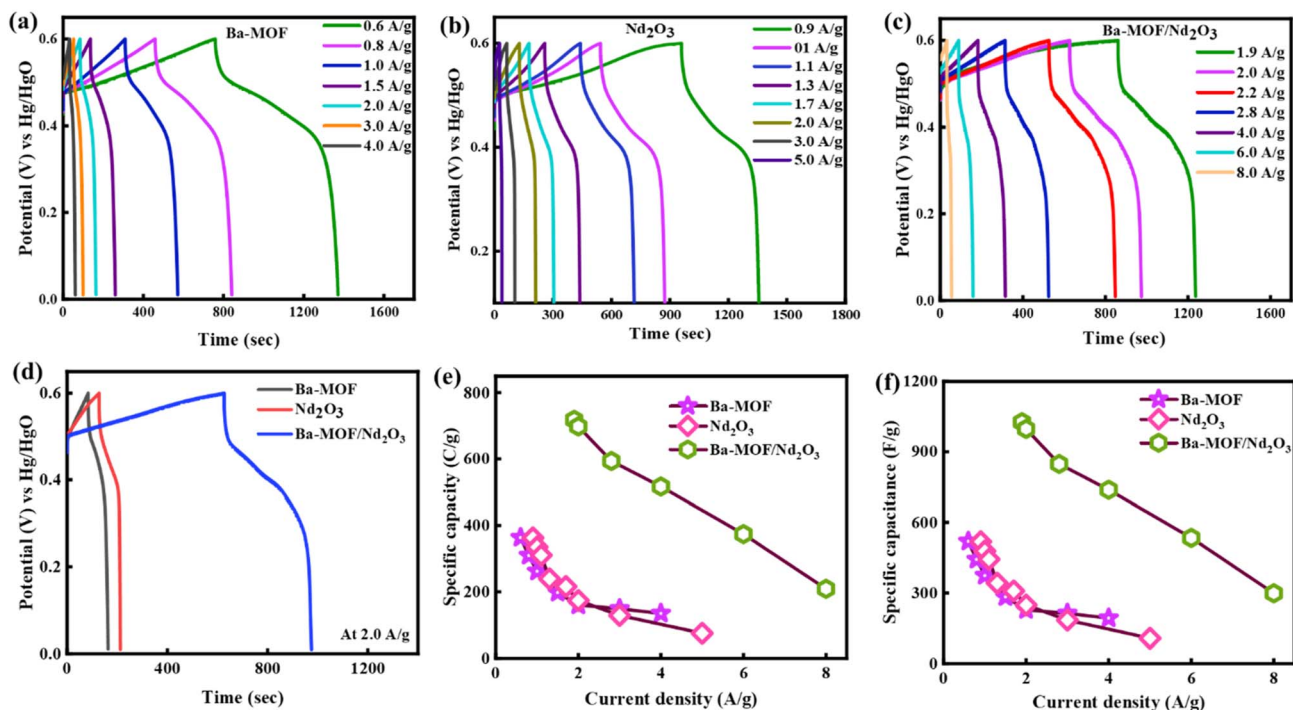


Fig. 4 GCD cycles at various current densities (a) Ba-MOF (b)  $\text{Nd}_2\text{O}_3$  (c) Ba-MOF/ $\text{Nd}_2\text{O}_3$ . (d) Comparative GCD at  $1.9 \text{ A g}^{-1}$ . (e)  $Q_s$  of fabricated electrodes at various current densities. (f)  $C_s$  of fabricated electrodes at various current densities.



### 3.2. Electrochemical characterization

**3.2.1 Half-cell measurements.** The electrochemical performance of Ba-MOF, Nd<sub>2</sub>O<sub>3</sub>, and Ba-MOF/Nd<sub>2</sub>O<sub>3</sub> was initially assessed in a half-cell setup with 1 M potassium hydroxide as the electrolyte. Cyclic voltammetry (CV) analysis was executed at various scan rates (1–40 mV s<sup>-1</sup>) between 0–0.7 V. Fig. 3(a–c) shows that the CV profile of the fabricated electrodes manifested distinct redox peaks characteristic of battery-grade behavior and stable faradaic reactions within the electrode materials.<sup>50</sup>

Notably, the Ba-MOF/Nd<sub>2</sub>O<sub>3</sub> composite exhibited higher current values and a larger area under the CV profile compared with Ba-MOF and Nd<sub>2</sub>O<sub>3</sub>, underscoring its enhanced electrochemical performance, as shown in the comparative graph (Fig. 3(d)). The variation in redox peak positions in the CV profile of electrodes arises from alteration of the electrode composition and interaction between Ba-MOF and Nd<sub>2</sub>O<sub>3</sub>. Incorporation of Nd<sub>2</sub>O<sub>3</sub> into the MOF matrix introduces new redox-capable centers and alters the electronic configuration surrounding the Ba sites. Moreover, the reduction peaks in the composite CV curves show prominent humps, which can be attributed to surface heterogeneity and the presence of multiple redox-active sites from both Ba-MOF and Nd<sub>2</sub>O<sub>3</sub>. These humps reflect the complex redox interactions and synergistic effect within the composite, where multiple redox processes occur at different potentials, enhancing its capacity. Additionally, the expanded CV of the composite at higher scans highlights its increased charge storage ability and enhanced electrochemical characteristics. Specific capacity was computed by employing the relation given below.<sup>51</sup>

$$Q_s = \frac{\int I \times dV}{m \times \nu} \quad (2)$$

Here,  $Q_s$  denotes specific capacity (C g<sup>-1</sup>), the integral term represents the area of the CV profile,  $m$  refers to the mass load, and  $\nu$  stands for the scan rate. The  $Q_s$  of pristine Ba-MOF and Nd<sub>2</sub>O<sub>3</sub> is relatively lower, whereas their composite feedback is significantly enhanced. Pristine Ba-MOF and Nd<sub>2</sub>O<sub>3</sub> exhibited specific capacities of 536 C g<sup>-1</sup> and 555 C g<sup>-1</sup>, correspondingly, while the Ba-MOF/Nd<sub>2</sub>O<sub>3</sub> composite achieved a much higher specific capacity of 1014 C g<sup>-1</sup> at the lowest scanning rate. This improvement results from a strong synergistic effect between Ba-MOF and Nd<sub>2</sub>O<sub>3</sub> in the composite structure. Nd<sub>2</sub>O<sub>3</sub> is a rare-earth metal oxide that possesses a high oxygen vacancy concentration and good redox reversibility, which can contribute to pseudocapacitive behavior. These oxygen vacancies facilitate faster ion diffusion and may enhance surface faradaic reactions during the charge–discharge process. However, when used alone, Nd<sub>2</sub>O<sub>3</sub> exhibits limited electrochemical performance owing to poor conductivity and a low surface area. In the composite form, Ba-MOF provides a porous and conductive framework that accommodates Nd<sub>2</sub>O<sub>3</sub> particles, while Nd<sub>2</sub>O<sub>3</sub> improves the electrochemical reactivity and conductivity of the MOF structure. This complementary interaction improves charge transfer kinetics and structural integrity. Therefore, the Ba-MOF/Nd<sub>2</sub>O<sub>3</sub> composite benefits from both components, with the porous nature of Ba-MOF enhancing ion transport and redox-active Nd<sub>2</sub>O<sub>3</sub> contributing to higher pseudocapacitance. This enhanced performance of the composite highlights its potential for superior energy storage applications. The value of  $Q_s$  and  $C_s$  of all the electrodes at different sweep rates is depicted in Fig. 3(e and f).

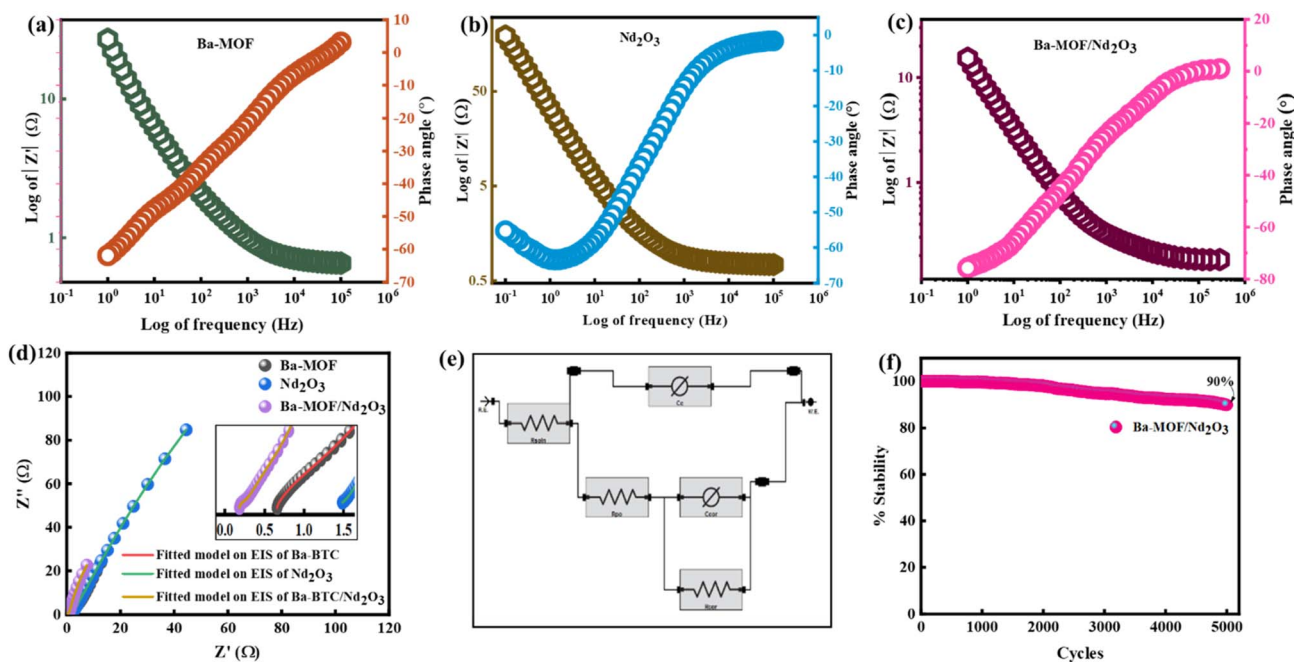


Fig. 5 (a) Bode plot of Ba-MOF. (b) Bode plot of Nd<sub>2</sub>O<sub>3</sub>. (c) Bode plot of Ba-MOF/Nd<sub>2</sub>O<sub>3</sub>. (d) Nyquist plot of fabricated electrodes with its zoomed part in the inset. (e) Fitted model circuit. (f) Cyclic stability of the composite.



Thereafter, GCD testing was conducted at a potential of 0.6 V across various current densities. The non-linear behavior in the discharging profile further reinforces the battery-grade characteristics of synthesized product, consistent with the confirmation from CV analysis, as portrayed in Fig. 4(a–c). Fig. 4(d) illustrates the comparative analysis of various electrodes at 2 A g<sup>-1</sup>. The prolonged discharge duration of the Ba-MOF/Nd<sub>2</sub>O<sub>3</sub> composite in comparison with Ba-MOF and Nd<sub>2</sub>O<sub>3</sub> alone highlights the enhanced energy storage capability of the composite, in agreement with the earlier CV analysis. The high-rate capability is highlighted by symmetrical responses under higher scans and current density. Additionally, the  $Q_s$  values were determined from GCD analysis by applying the subsequent expression:<sup>52</sup>

$$Q_s = \frac{I \times \Delta t}{m} \quad (3)$$

Here,  $I$  stands for current,  $\Delta t$  refers to the discharge profile, and  $m$  corresponds to mass loading of the fabricated material.

The Ba-MOF and Nd<sub>2</sub>O<sub>3</sub> achieved  $Q_s$  values of 363 C g<sup>-1</sup> and 362 C g<sup>-1</sup> at 0.6 A g<sup>-1</sup> and 0.9 A g<sup>-1</sup>, respectively, reflecting the inherent electrochemical behavior of each material. In contrast, the Ba-MOF/Nd<sub>2</sub>O<sub>3</sub> composite exhibited a significantly enhanced  $Q_s$  of 718 C g<sup>-1</sup> at 1.9 A g<sup>-1</sup>, highlighting the superior performance of the composite. This enhancement in the specific capacity is primarily due to synergistic effects between the Ba-MOF and Nd<sub>2</sub>O<sub>3</sub>, which combine the individual advantages of both materials. These synergistic effects result in an increased number of active sites for redox reactions, enhanced electron conductivity, and more efficient ion diffusion within the composite structure.

Additionally, the composite's improved structural integrity contributes to better cyclic stability, reducing material degradation over time and enabling more effective charge storage. The enhanced conductivity minimizes internal resistance, leading to faster electron transport and more efficient energy transfer during charge–discharge cycles. Besides, the porous structure of the composite likely provides a larger surface area

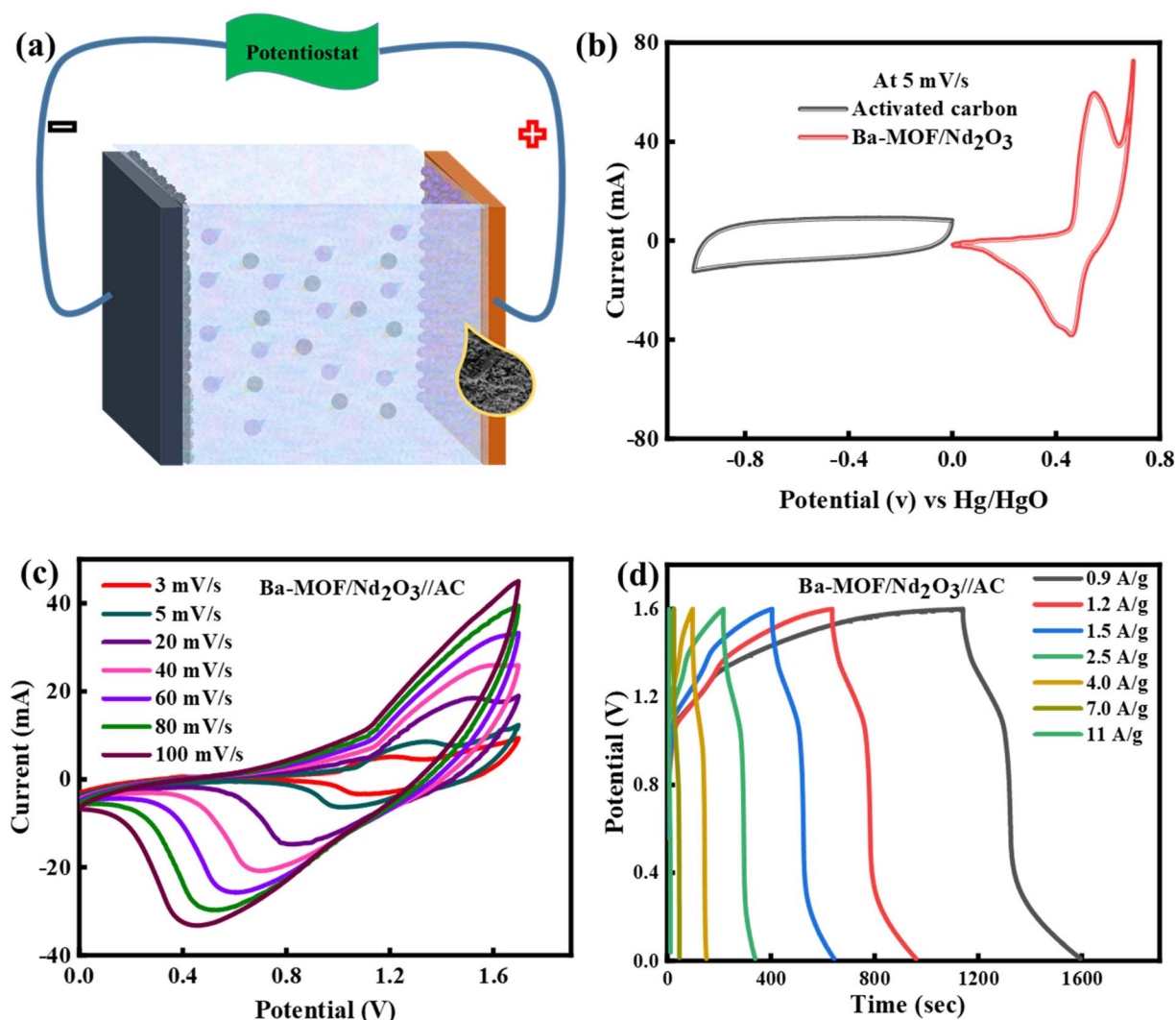


Fig. 6 (a) Schematic of the device. (b) CV curve of both battery grade and capacitive electrodes at 5 mV s<sup>-1</sup> (c) CV graph of the assembled device (Ba-MOF/Nd<sub>2</sub>O<sub>3</sub>//AC). (d) GCD investigation of the device.



and better electrolyte penetration, promoting faster ion diffusion and more uniform charge distribution. These combined factors contribute to the composite's significantly higher specific capacity compared with the individual materials, making it a more effective electrode for energy storage applications. The calculated  $Q_s$  and  $C_s$  values from GCD analysis are demonstrated in Fig. 4(e and f).

To investigate the conductive behavior and associated parameters of the fabricated electrode materials, EIS measurements were carried out over a frequency range of 0.1–100 kHz with an applied voltage of 10 mV. Fig. 5(a–c) is the Bode plot for Ba-MOF,  $\text{Nd}_2\text{O}_3$ , and their composite, where the log of impedance magnitude and phase angle are plotted against the log of frequency. The double y-axis plot reveals the frequency-dependent behavior of both impedance and phase shift. The composite material delivered the lowest impedance at a lower frequency range, demonstrating the best performance compared with Ba-MOF and  $\text{Nd}_2\text{O}_3$ , offering superior electrochemical performance. This lower impedance suggests that the synergy between Ba-MOF and  $\text{Nd}_2\text{O}_3$  optimizes ion transport and reduces energy losses more effectively than either individual component. At the intermediate frequency region, the slope of the magnitude of the impedance decreases, reflecting

an increase in resistive dominance. At higher frequencies, the impedance magnitude levels off and becomes nearly parallel to the x-axis, indicating pure resistive behavior, corresponding to the equivalent series resistance (ESR), which will be further discussed in the Nyquist plot. Similarly, the composite shows the maximum value of the phase angle in the Bode plot (near  $-90^\circ$ ), indicating more capacitive dominant behavior compared with an individual, and is beneficial for energy storage applications. Fig. 5(d) is the Nyquist plot with the fitted model, which demonstrates significant improvement in the conductivity of the Ba-MOF after the incorporation of  $\text{Nd}_2\text{O}_3$ . The inset of Fig. 5(d) particularly emphasizes this enhancement at high frequencies. The Ba-MOF/ $\text{Nd}_2\text{O}_3$  exhibited the smallest equivalent series resistance (ESR =  $0.35 \Omega$ ) compared with the individual samples owing to improved electron transport and enhanced ion diffusion. The combination of two materials creates more efficient pathways for both ions and electrons, reducing internal resistance. Additionally, the optimized interface between Ba-MOF and  $\text{Nd}_2\text{O}_3$  minimizes charge transfer resistance, contributing to the lower ESR value. The Nyquist plot displays no noticeable semicircle, suggesting a low interfacial resistance to charge transfer at the electrode surface. A shorter linear segment in the composite points to decreased

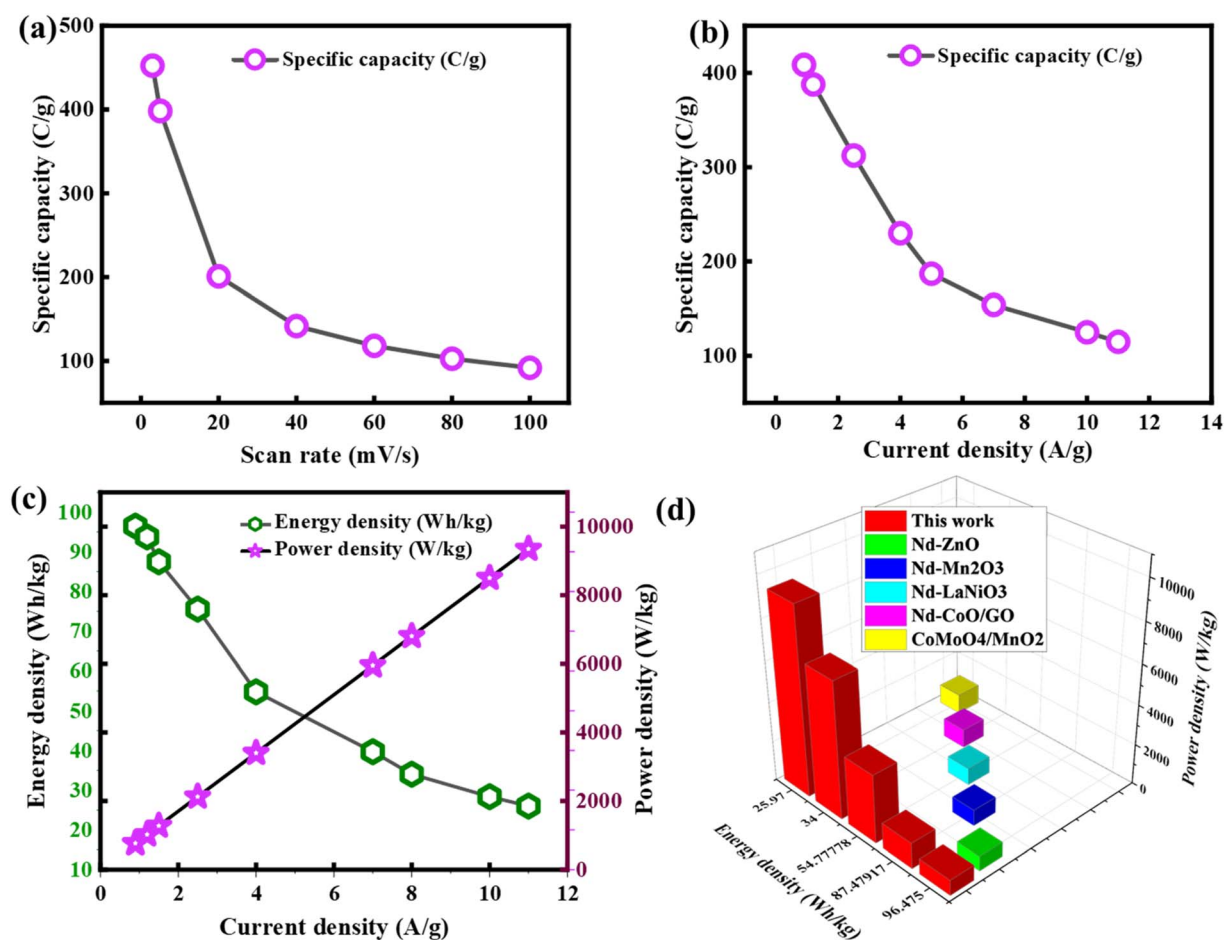


Fig. 7 (a)  $Q_s$  of the assembled device at various scan rates. (b)  $Q_s$  of the assembled device at various current densities. (c) Energy vs. power plot of the device. (d) Comparison with previous literature.

Warburg resistance ( $W_b$ ) compared with Ba-MOF and  $\text{Nd}_2\text{O}_3$  alone, reflecting improved ion transport. This improved ion transport likely results from an interconnected structure in the composite, which enhances charge transfer and supports faster charge/discharge rates, boosting its overall electrochemical performance. Fig. 5(e) shows the circuit of the fitted model on the EIS data points of Ba-MOF,  $\text{Nd}_2\text{O}_3$ , and Ba-MOF/ $\text{Nd}_2\text{O}_3$ . Additionally, cyclic stability was tested over 5000 cycles, and the composite retained 90% of its initial capacity, as presented in Fig. 5(f). The results from CV, GCD, and EIS analysis highlight the exceptional electrochemical performance of Ba-MOF/ $\text{Nd}_2\text{O}_3$ , positioning it as a suitable contender for future hybrid energy storage technology.

**3.2.2 Full-cell measurements.** The capability of the synthesized material was further examined by using the best-performing electrode (Ba-MOF/ $\text{Nd}_2\text{O}_3$ ) as an anodic electrode, along with AC in 1 M KOH. The cyclic voltammetric study was conducted across a 3–100  $\text{mV s}^{-1}$  scan rate, with a potential of 0–1.7 V. The schematic complete-cell setup and individual CV profile of Ba-MOF/ $\text{Nd}_2\text{O}_3$  and AC at 5  $\text{mV s}^{-1}$  are depicted in Fig. 6(a and b). The CV curves of the cell shown in Fig. 6(c) demonstrate a hybrid-shape profile, indicating a combination

of battery-like and capacitive behavior. This hybrid shape reflects the synergistic combination of the faradaic redox reaction at the Ba-MOF/ $\text{Nd}_2\text{O}_3$  electrode and the double-layered capacitance behavior of the AC electrode. The symmetric response at high scan rates underscores its excellent rate capability and electrochemical stability.

Additionally, GCD assessment was performed at 1.6 V potential over a broad regime of current densities (0.9–11  $\text{A g}^{-1}$ ) to evaluate its charge–discharge characteristics, as depicted in Fig. 6(d). The GCD profiles show linear segments typical of capacitive behavior, while the minor inflections in the discharge portion point to the participation of battery-like redox reactions. The device demonstrated an impressive  $Q_s$  of 452  $\text{C g}^{-1}$  and 408  $\text{C g}^{-1}$  at the lowest scan rate and current density, respectively. Fig. 7(a and b) demonstrated the variation of  $Q_s$  with various scan rates and current densities. Key electrochemical performance metrics namely, energy density and power density are calculated with the following relations.<sup>53</sup>

$$E_d = \frac{Q_s \times \Delta V}{2 \times 3.6} \quad (4)$$

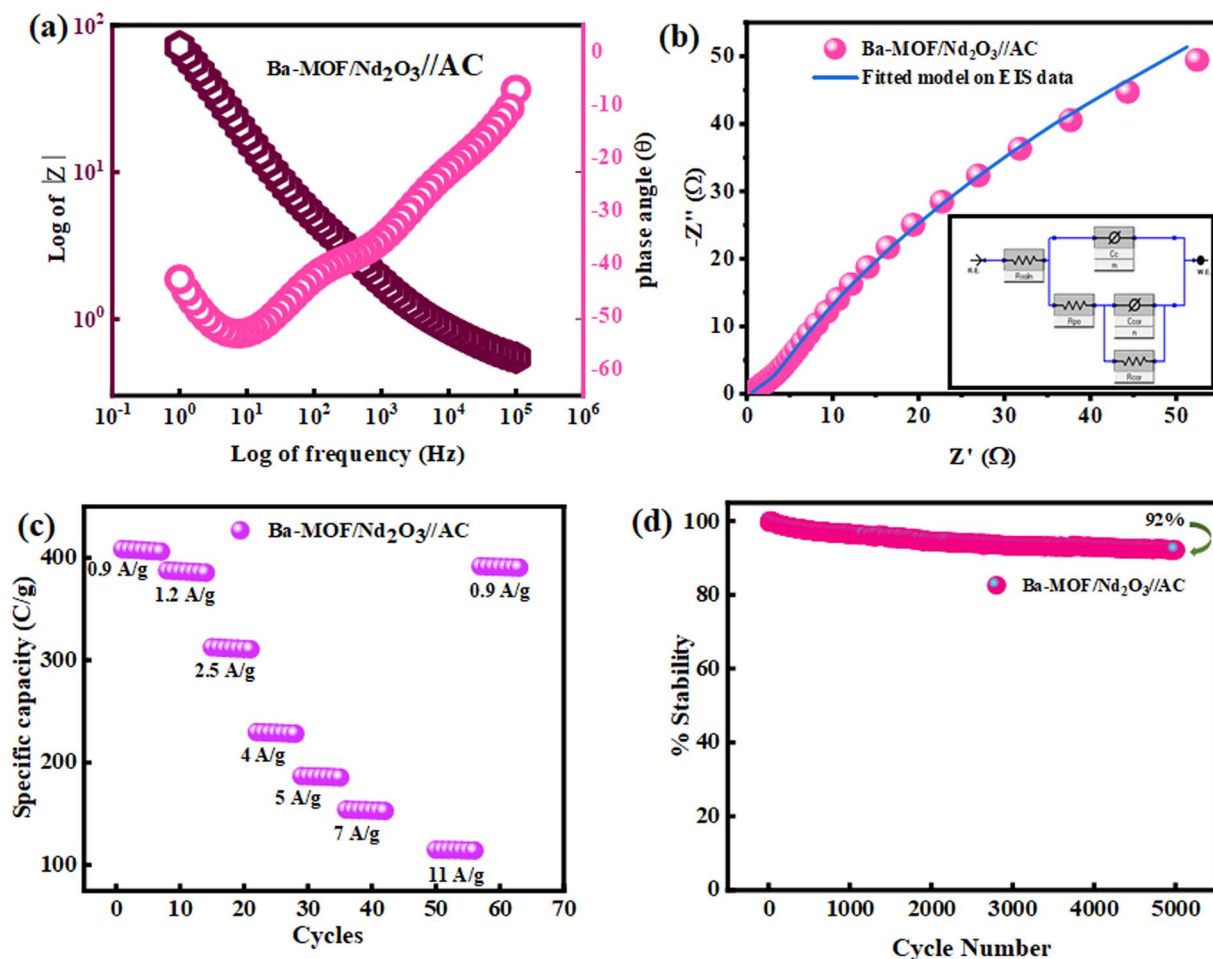


Fig. 8 (a) Bode plot of the device. (b) Nyquist plot of the device. (c) Rate capability of the device. (d) Cyclic stability of the device.



$$P_d = \frac{3600 \times E_s}{\Delta t} \quad (5)$$

In the aforementioned relations,  $\Delta V$  is the potential window, while  $\Delta t$  represents the discharge time. The device attained an impressive  $E_d$  of 96 Wh kg<sup>-1</sup> and a  $P_d$  of 765 Wh kg<sup>-1</sup> at 0.9 A g<sup>-1</sup>. Furthermore, the device accomplished an exceptional maximum  $P_d$  of 9350 W kg<sup>-1</sup> while sustaining the  $E_d$  of 25.9 Wh kg<sup>-1</sup> at 11 A g<sup>-1</sup>. The dependence of energy and power densities on applied current densities is shown in Fig. 7(c), while Fig. 7(d) displays the Ragone plot comparing the fabricated cell to the reported work.<sup>54–58</sup> This evaluation underscores the superior performance of our fabricated device, establishing it as a suitable contender for advanced HSCs.

To assess conductivity and the associated parameters, EIS measurements were performed within a frequency window of 0.1 to 100 kHz at an applied voltage of 10 mV. The Bode plot for Ba-MOF/Nd<sub>2</sub>O<sub>3</sub>//AC shows a small value of impedance at the low-frequency regime (Fig. 8(a)). The intermediate frequency range shows contributions from both resistive and capacitive behavior, while the response transitions to a purely resistive behavior at higher frequencies. Fig. 8(b) presents the Nyquist

plot with its fitted model, revealing a small ESR (0.52 Ω), with an insignificant value of  $R_{ct}$ . The low ESR highlights the better intrinsic conductivity of the device, ensuring efficient electron/ion flow with minimal resistance. The negligible  $R_{ct}$  reflects highly effective transfer at the electrode–electrolyte interface. Furthermore, the rate capability of the device was evaluated, demonstrating 96% retention, as presented in Fig. 8(c). However, a decrease in capacity is observed with increasing current densities, which is common in battery-grade materials owing to limited ion diffusion time. The device exhibits excellent rate reversibility when the current density is returned to its original value. In addition, stability testing across 5000 consecutive cycles revealed an impressive retention rate of 92%, as illustrated in Fig. 8(d). The slight decline in capacity retention (8% over 5000 cycles) may be attributed to structural distortion in the material, which could lead to a gradual loss of electrochemical activity. Prolonged electrolyte exposure may also contribute to the partial dissolution of active species, particularly from the Ba-MOF phase, thereby compromising long-term stability. Moreover, repetitive charge–discharge cycling could induce interfacial degradation at the active

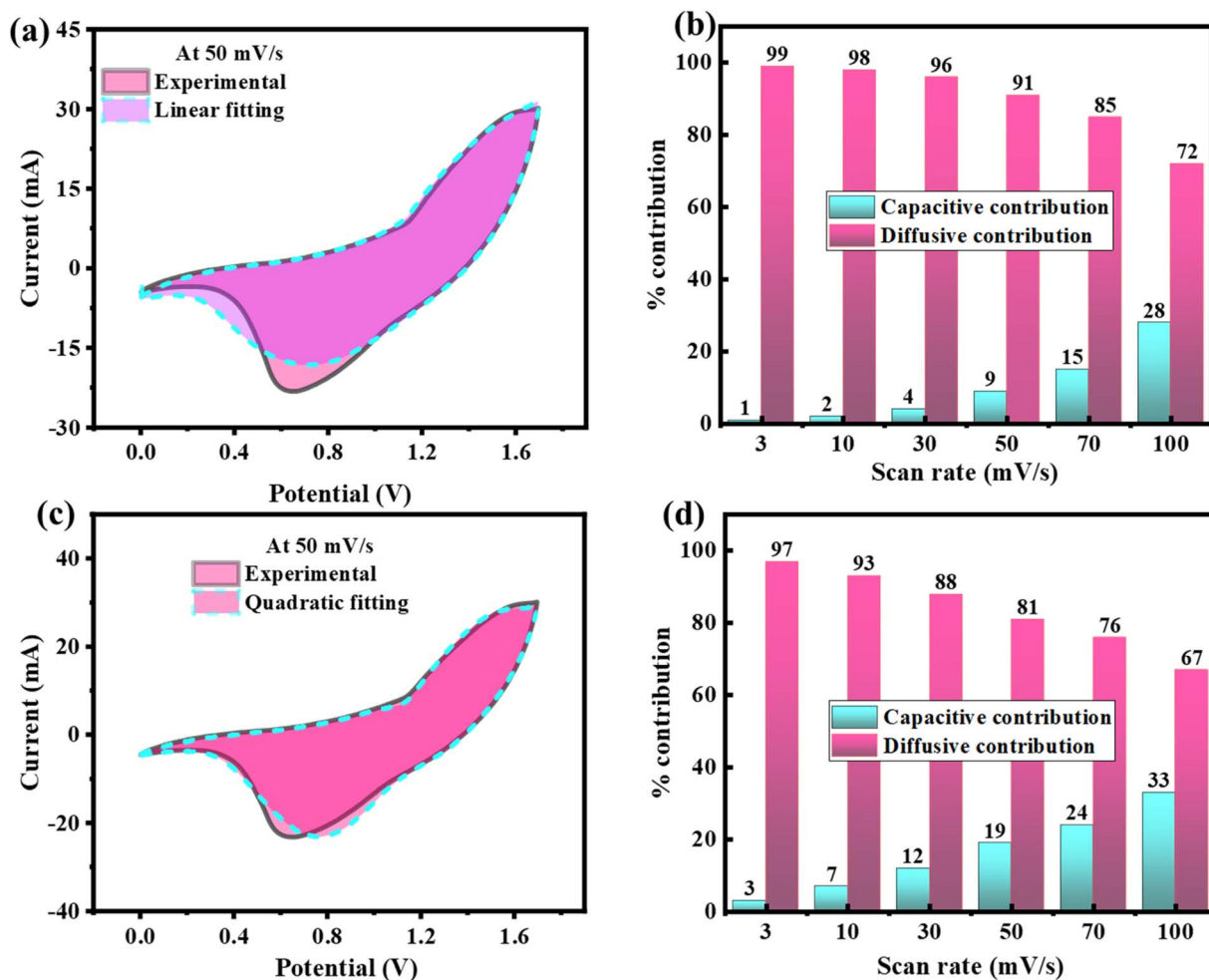


Fig. 9 (a) Linear model fitting of experimental data. (b) Bar graph of capacitive and diffusive contributions by the linear model. (c) Quadratic model fitting of experimental data. (d) Bar graph of capacitive and diffusive contributions by the quadratic model.



material–current collector boundary, resulting in incremental increases in internal resistance. These outcomes highlight the continuous and stable electrochemical performance of the device.

### 3.3. Semi-empirical analysis

To analyze the capacitive and diffusion-controlled charge storage pathway of the device, two semi-empirical approaches were utilized: linear and quadratic models. The models were utilized on the same device, but the quadratic one proved to be more accurate, closely aligning with the observed behavior.

The total current is determined as a sum of two components:  $I_{NF} = k_1v$  is attributed to non-faradaic current, while  $I_F = k_2v^{1/2}$  demonstrates faradaic current. These currents are determined by employing the following relation.<sup>59</sup>

$$I(v, V) = k_1v + k_2v^{1/2} \quad (6)$$

In this equation,  $v$  corresponds to the scan rate, while  $k_1$  and  $k_2$  represent the regression parameters. The term  $k_1v$  refers to capacitive contributions, while  $k_2v^{1/2}$  represents the process governed by ion diffusion. Fig. 9(a) demonstrates the linear fitting of the experimental data for the capacitive and diffusive contributions at 50 mV s<sup>-1</sup>. Although the linear model is effective in capturing basic trends, it struggles when analyzing larger data segments or regions near peaks. Fig. 9(b) showcases the substantial performance of the electrode through a linear model bar graph. The plot highlights the extent to which capacitive and diffusion-driven behaviors influence the charge storage process under varying scan conditions.

To overcome the shortcomings of the linear model, a diffusive correction was integrated. It resulted in a quadratic model, providing a more precise representation of the underlying phenomenon.<sup>60</sup>

$$I(v, V) = \beta_1v + \beta_2v^{1/2} + \beta_3v^{3/2} \quad (7)$$

In the above equation,  $\beta_i$  ( $i = 1, 2, 3$ ) are regression parameters,  $\beta_1v$  captures the combined effects of capacitive and pseudocapacitive behavior, whereas  $\beta_2v^{1/2}$  and  $\beta_3v^{3/2}$  account for the diffusive behavior. The quadratic fit depicted in Fig. 9(c) exhibits a significantly improved correlation with the experimental data, highlighting its effectiveness in capturing the observed results. Fig. 9(d) showcases the substantial performance of the electrode through a bar graph. The graph effectively illustrates the respective roles of surface-controlled and ion-diffusion mechanisms in charge retention under various scan rates. The bar graph of linear and quadratic models reveals a progressive decline in diffusive contribution as the scan rate increases. This phenomenon is likely due to the limited time available to complete the redox reaction.

## 4. Conclusion

In this study, we successfully synthesized Ba-MOF/Nd<sub>2</sub>O<sub>3</sub> composite by the hydrothermal approach. Characterization techniques such as XRD, SEM, and EDX were employed to

investigate the crystalline structure, morphological features, and elemental distribution of the fabricated material. The electrochemical performance was assessed, showing that Ba-MOF, Nd<sub>2</sub>O<sub>3</sub>, and their composite achieved 363 C g<sup>-1</sup>, 362 C g<sup>-1</sup>, and 718 C g<sup>-1</sup>, respectively, at the lowest current density. Based on the elevated capability of the composite, a hybrid device was assembled using Ba-MOF/Nd<sub>2</sub>O<sub>3</sub> as an anodic electrode and AC as a cathodic electrode. The cell demonstrated a  $Q_s$  of 408 C g<sup>-1</sup> at the lowest current density, with an  $E_d$  of 96 Wh kg<sup>-1</sup> and  $P_d$  of 9350 W kg<sup>-1</sup>. Moreover, it presented impressive cyclic stability by maintaining 92% of its initial capacity even after 5000 consecutive iterations. To further understand the device's behavior, two distinct semi-empirical models were utilized and their results were evaluated against the experimental findings. The comprehensive electrochemical characteristics presented in this study highlight the potential of Ba-MOF/Nd<sub>2</sub>O<sub>3</sub> as a favorable electrode material for future hybrid supercapacitor applications. In future work, the electrochemical performance of the Ba-MOF/Nd<sub>2</sub>O<sub>3</sub> composite could be further enhanced through strategies such as interfacial engineering, or the introduction of conductive networks to improve charge transport and stability.

## Data availability

All the data are provided in the article.

## Conflicts of interest

The authors declare that there are no conflicts of interest.

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